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1. Introduction

The oceans cover about 71% of the Earth's surface and contain 97% of the Earth's water (see Trenberth 2001). Through their fluid motions, their high heat capacity, and their ecosystems, the oceans play a central role in shaping the Earth's climate and its variability. Changes in sea level have major impacts on coastal regions and storm surges. Accordingly, it is vital to monitor and understand changes in the oceans and their effects on weather and climate, and improve the verisimilitude of model ocean simulations. In this introduction, we outline these aspects and provide a justification for the ocean variables that should be observed and the networks and methods whereby this is achieved.

The most important characteristic of the oceans is that they are wet and, while obvious, this is sometimes overlooked. Water vapor, evaporated from the ocean surface, provides latent heat energy to the atmosphere during the precipitation process. In units of 10^3 km^3 per year, evaporation E over the oceans (413) exceeds precipitation P (373), leaving a net of 40 units of moisture transported onto land as water vapor. On average, this flow must be balanced by a return flow over and beneath the ground through river and stream flows, and subsurface ground water flow. The average precipitation rate over the oceans exceeds that over land (113) by a factor of 1.4 (allowing for the differences in areas), and precipitation exceeds evapotranspiration over land by this same amount (40) (Trenberth et al. 2007a). This flow into the oceans occurs mainly in river mouths and is a substantial factor in the salinity of the oceans, thus affecting ocean density and currents. A simple calculation of the volume of the oceans of about 1335×10^6 km^3 and the through-flow fluxes of E and P implies an average residence time of water in the ocean of over 3,000 years.

Changes in phase of water, from ice to liquid to water vapor, affect the storage of heat. However, even ignoring these complexities, many facets of the climate can be deduced simply by considering the heat capacity of the different components of the climate system. The total heat capacity considers the mass involved as well as its capacity for holding heat, as measured by the specific heat of each substance.

The atmosphere does not have much capability to store heat. The heat capacity of the global atmosphere corresponds to that of only a 3.5 m layer of the ocean (see Trenberth and Stepaniak 2004). However, the depth of ocean actively involved in climate is much greater than that. The specific heat of dry land is roughly a factor of 4.5 less than that of sea water (for moist land the factor is probably closer to 2). Moreover, heat penetration into land is limited by the low thermal conductivity of the land surface; as a result only the top two meters or so of the land typically play an active role in heat storage and release (e.g., as the depth for most of the variations over annual time scales). Accordingly, land plays a much smaller role than the ocean in the storage of heat and in providing a memory for the climate system. Major ice sheets over Antarctica and Greenland have a large mass but, like land, the penetration of heat occurs primarily through conduction so that the mass experiencing temperature changes from year to year is small. Hence, ice sheets and glaciers do not play a strong role in heat capacity, while sea ice is important where it forms. Unlike land, however, ice caps and ice sheets melt, altering sea level albeit fairly slowly.

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The seasonal variations in heating penetrate into the ocean through a combination of radiation, convective overturning (in which cooled surface waters sink while warmer more buoyant waters below rise) and mechanical stirring by winds. These processes mix heat through the mixed layer, which, on average, involves about the upper 90 m of ocean. The thermal inertia of a 90 m layer can add a delay of about 6 years to the temperature response to an instantaneous change (this time corresponds to an exponential time constant in which there is a 63% response toward a new equilibrium value following an abrupt change). As a result, actual changes in climate tend to be gradual. With its mean depth of about 3800 m, the total ocean would add a delay of 230 years to the response if rapidly mixed. However, mixing is not a rapid process for most of the ocean so that in reality the response depends on the rate of ventilation of water between the well-mixed upper layers of the ocean and the deeper, more isolated layers that are separated by the thermocline (the ocean layer exhibiting a strong vertical temperature gradient). The rate of such mixing is not well established and varies greatly geographically. An overall estimate of the delay in surface temperature response caused by the oceans is 10–100 years. The slowest response should be in high latitudes where deep mixing and convection occur, and the fastest response is expected in the tropics. Consequently, the oceans are a great moderating effect on climate changes.

Wind blowing on the sea surface drives the large-scale ocean circulation in its upper layers. The oceans move heat around through convection and advection (in which the heat is carried by the currents, whether small-scale short-lived eddies or large-scale currents). Hence ocean currents carry heat and salt along with the fresh water around the globe. The oceans therefore store heat, absorbed at the surface, for varying durations and release it in different places, thereby ameliorating temperature changes over nearby land and contributing substantially to variability of climate on many time scales.

The ocean thermohaline circulation (THC), which is the circulation driven by changes in sea water density arising from temperature (thermal) and salt (haline) effects, allows water from the surface to be carried into the deep ocean, where it is isolated from atmospheric influence and hence it may sequester heat for periods of a thousand years or more. The Meridional Overturning Circulation (MOC) involves not only the THC but also wind-driven currents. The oceans also absorb carbon dioxide and other gases and exchange them with the atmosphere in ways that change with ocean circulation and climate change. In addition, it is likely that marine biotic responses to climate change will result in subsequent changes that may have further ramifications, for instance by changing ocean color and penetration of sunlight into the ocean.

2. An example: The annual cycle

In the subtropics, the oceans typically take up in excess of 100 W m^{-2} in the summer months and give it to the atmosphere in winter mostly in the form of evaporation of moisture. This cools the ocean while eventually warming the atmosphere when released as latent heat in precipitation (Trenberth and Stepaniak 2003, 2004; Fasullo and Trenberth 2008a,b). In mid-latitudes, air coming off the ocean is warmer than the land in winter and cooler in summer, giving rise to refreshing sea breezes and moderating temperatures. Regions influenced by the ocean in this way are referred to as having maritime climates. On average there is a substantial net flow of energy from oceans to land of about 2.2 Petawatts, mainly in the Northern Hemisphere in winter (Fasullo and Trenberth 2008a).

An example of the role of the oceans in moderating temperature variations is the contrast in the mean annual cycle of surface temperature between the northern hemisphere (NH) (60.7% water) and southern hemisphere (SH) (80.9% water). The amplitude of the 12-month cycle between 40 and 60° latitude ranges from <3°C in the SH to about 12°C in the NH. Similarly, in mid-latitudes from 22.5–67.5° latitude, the average lag in temperature response relative to peak solar radiation is 32.9 days in the NH versus 43.5 days in the SH (Trenberth 1983), reflecting the differences in thermal inertia.

3. The oceans and sea ice

Sea ice is an active component of the climate system and varies greatly in areal extent with the seasons, but only at higher latitudes. In the Arctic where sea ice is confined by the surrounding continents, mean sea ice thickness is 3–4m and multi-year ice can be present. Around Antarctica the sea ice is unimpeded and spreads out extensively, but as a result the mean thickness is typically 1–2 m. Sea ice caps the ocean and interferes with ocean-atmosphere exchanges of heat, moisture, and other gases. Melting sea ice freshens the ocean and diminishes the density. However, its greatest impact is through changes in albedo of the surface; the much darker ocean surface absorbs more solar radiation, further warming the ocean and leads to the ice-albedo positive feedback that amplifies initial perturbations. Diminished sea ice also increases moisture fluxes into the atmosphere, which may increase fog and low cloud, adding further complexity to the net albedo change. Ocean currents transport sea ice, which is also subject to stresses from surface wind.

In the Arctic, IPCC (2007) reports that sea ice has decreased and thinned since 1970, with largest decreases of 20% in late summer from 1979 to 2005. In September 2007 the previous lowest value was exceeded by over another 20%, to create an all time record low extent, suggesting that there are real prospects for the Arctic becoming ice free in late summer by about the 2040s (Holland et al. 2006). In 2008, values were not quite as low as 2007 but still much lower than years prior to 2007. Overall sea ice loss in September is about 40% of the values in the 1970s.

4. Coupled ocean-atmosphere interactions

Understanding the climate system becomes more complex as the components interact. El Niño events are a striking example of a phenomenon that would not occur without interactions between the atmosphere and ocean. El Niño events involve a warming of the surface waters of the tropical Pacific. Ocean warming takes place from the International Dateline to the west coast of South America and results in changes in the local and regional ecology. Historically, El Niño events have occurred about every 3–7 years and alternated with the opposite phases of below average temperatures in the tropical Pacific, dubbed La Niña. In the atmosphere, a pattern of change called the Southern Oscillation is closely linked with these ocean changes, so that scientists refer to the total phenomenon as ENSO. Then El Niño is the warm phase of ENSO and La Niña is the cold phase.

The strong sea surface temperature (SST) gradient from the warm pool in the western tropical Pacific to the cold tongue in the eastern equatorial Pacific is maintained by the westward-flowing trade winds, which drive the surface ocean currents and determine the pattern of upwelling of cold nutrient-rich waters in the east. Because of the Earth's rotation, easterly winds along the equator deflect currents to the right in the NH and to the left in the SH and thus away from the equator, creating upwelling along the equator. Low sea level pressures are set up over the warmer waters while higher pressures occur over the cooler regions in the tropics and subtropics. The moisture-laden winds tend to blow toward low pressure so that the air converges, resulting in organized patterns of heavy rainfall and a large-scale overturning along the equator called the Walker Circulation. Because convection and thunderstorms preferentially occur over warmer waters, the pattern of SSTs determines the distribution of rainfall in the tropics, and this in turn determines the atmospheric heating patterns through the release of latent heat. The heating drives the large-scale monsoonal-type circulations in the tropics, and consequently determines the winds. If the Pacific trade winds relax, the ocean currents and upwelling change, causing temperatures to increase in the east, which decreases the surface pressure and temperature gradients along the equator, and so reduces the winds further. This positive feedback leads to the El Niño warming persisting for a year or so, but the ocean changes also sow the seeds of the event's demise. The changes in the ocean currents and internal waves in the ocean lead to a progression of colder waters from the west that may terminate the El Niño and lead to the cold phase La Niña in the tropical Pacific.

The El Niño develops as a coupled ocean–atmosphere phenomenon and, because the amount of warm water in the tropics is redistributed, depleted and restored during an ENSO cycle, a major part of the onset and evolution of the events is determined by the history of what has occurred one to two years previously. This means that the future evolution is potentially predictable for several seasons in advance.

5. Sea level

Another role of oceans in climate that has major impacts on multi-decadal time-scales is sea level rise. Climate models estimate that there is a radiative imbalance at the top-of-the-atmosphere of about 0.6 to 1 W m^{-2} (Hansen et al. 2005) owing to increases of greenhouse gases, notably carbon dioxide, in the atmosphere. Recent estimates place this value after 2000 at about 0.9 W m^{-2} (Fasullo and Trenberth 2008a). This has increased from a very small imbalance only 40 years ago. Where is this heat going? Some heat melts glaciers and ice, contributing mass to the ocean and thus eustatic sea level rise (Levitus et al. 2001). Some heat enters the ocean and increases temperatures, leading to expansion of the ocean and thus what is known as thermosteric sea level rise (Hansen et al. 2005). Only very small amounts of heat enter the land, as noted above. Levitus et al. (2000) estimated that the heat content of the oceans increased on average by about 0.3 W m^{-2} over the past several decades, but in a somewhat irregular fashion. Larger rates in recent decades are discussed below. Hence the main candidate for a heat sink is the oceans, and sea level rise synthesizes both expansion and added mass from melting of ice elements. Hence it is an excellent indicator of warming.

Sea level observations. Sea level was estimated to have risen throughout the 20^{th} century by 1.8±0.5 mm/year (Church et al. 2004; White et al. 2005), and about 0.3 mm/year is from isostatic rebound. However, the rate accelerated from the 1992 to 2009 when accurate satellite-based global measurements of sea level from TOPEX/Poseidon and Jason altimetry are available (Church et al. 2004), and averages about 3 mm/year (e.g., Willis et al. 2008; Domingues et al. 2008). The trend after 1993 is remarkably linear with two major short-term perturbations. There was an increase above the trend line in 1997-98 associated with the major 1997-98 El Niño event, and a dip below the line in 2007-08 with the recent La Niña. These fluctuations in sea level with El Niño come partly from changes in ocean heat content, but mainly arise from changes in ocean mass when water is evaporated from the ocean (as it loses heat) and is precipitated on land in the changing precipitation patterns (Trenberth et al. 2002b). From regressions (Gu et al. 2007), the observed 1.5°C drop in Niño 3.4 SSTs for 6 months from October 2007 to March 2008 implies an increase in rainfall over land in the tropics (±25°) to such an extent as to lower sea level by 6.0 mm; hence the 2007-08 La Niña is responsible for the recent slowdown in sea level rise.

Land. Estimated contributions to sea level from longer-term changes in storage of water on land in reservoirs and dams may account for –0.55 mm/yr sea level equivalent (Chao et al. 2008), but these are compensated for by ground water mining, urbanization, and deforestation effects. This obviously depends on the time frame, but the net sum of land effects is thought to be small (Ngo-Duc et al. 2005; Domingues et al. 2008).

Ocean heat content. The steric contribution from thermal expansion is based mostly on the analysis of the historical record (e.g., Levitus et al. 2000, 2001). Yet that record is based on sub-surface ocean measurements which are inadequate in many areas prior to about 2002; for instance little or no sampling over many parts of the southern oceans (Wunsch et al. 2007; Fasullo and Trenberth 2008b; Gille 2008; Lyman and Johnson 2008). The ocean multivariate analyses are considered much more reliable after the introduction of satellite altimetry in 1992 (Lyman and Johnson 2008). Moreover considerable uncertainty was revealed in the record from expendable bathy thermographs (XBTs) and how they match up with soundings from ARGO floats (Gouretski and Koltermann 2007), and indicated that revisions in drop rates for XBTs were warranted. Hence, many analyses prior to about 2008 of ocean heat content are now obsolete as they did not account for errors in the fall rate of XBTs (Gouretski and Koltermann 2007; Wijffels et al. 2008). For instance Jevrejeva et al. (2008) reexamined sea level rise from island and coastal tide gauge stations and ocean heat content but used uncorrected values of the latter, and their results highlight the spurious nature of the variability in ocean heat content prior to recent corrections.

Several new reanalyses have been made of the ocean heat content based upon corrected XBT fall rates and other adjustments to the basic data, which tend to remove a lot of decadal variability, but retain the overall rate of rise in sea level of 1.6±0.2 mm/yr from 1961 to 2003 (Domingues et al. 2008; Wijffels et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009). Gille (2008) provides evidence that warming of the southern oceans is real in spite of the data shortcomings. The IPCC in the Fourth Assessment Report (AR4) (IPCC 2007) did not consider that a statement about possible acceleration of sea level rise was possible owing to the substantial decadal variability that has now been greatly reduced with the reprocessing of XBT data.

Moored arrays of buoys such as the TAO/TRITON array in the tropical Pacific have greatly helped ocean sampling and, beginning about 2000, ARGO floats have provided soundings of salinity and temperature from a depth of about 2000 m to the surface with increasing global coverage. Between 2003 and 2005, early estimates of ocean heat content suggested a downturn (Lyman et al. 2006), while sea level continued to rise at similar rates, so that the in situ record was incompatible with satellite altimetry (Lombard et al. 2006). This inconsistency stemmed partly from ARGO float data problems that have now supposedly been corrected or omitted (Willis et al. 2007). Even so, since 2003 there appears to have been a slow down in the rise of ocean heat (Willis et al. 2008; Cazenave et al. 2009) although sampling was found to be inadequate (Leuliette and Miller 2009) in the earlier Willis et al (2008) ARGO data analysis.

Land ice melt and salinity. A number of studies have highlighted changes in salinity. Changes in the freshwater balance of the Atlantic Ocean over the past four decades were revealed by Dickson et al. (2002) and Curry et al. (2003) who found a freshening in the North Atlantic and also south of 25°S, while salinity increased in the tropics and subtropics, especially in the upper 500 m. The implication is that there have been substantial increases in moisture transport by the atmosphere from the subtropics to higher latitudes, perhaps in association with changes in atmospheric circulation, such as the North Atlantic Oscillation (NAO). If this is the main process of importance then it has small effects on global mean sea level as fresh water is redistributed. However, Antonov et al. (2002) suggest that there is a secular decrease in overall ocean salinity, raising questions about the role of melting glaciers in sea level rise. Changes in salinity affect density and thus contribute a small halosteric contribution to sea level rise (Willis et al. 2008). Wadhams and Munk (2004) suggested that the 20th century eustatic rise was 0.6 mm/yr. Updated estimates of contributions from glaciers and small ice caps and from the ice sheets of Antarctica and Greenland (e.g., Krabill et al. 2004), were summarized by IPCC (2007) to have a eustatic sea level rise of about 1.2 mm/yr from 1992 to 2003. Since 2003 the eustatic component appears to have accelerated with new assessments from glaciers (Meier et al. 2007) of ~1 mm/yr and from the major ice sheets (Wouters et al. 2008; Rignot et al. 2008; Domingues et al 2008), which also contribute ~1 mm/yr.

A comprehensive synthesis of the (uncorrected) ocean observations in a model framework by the German Estimating the Circulation and Climate of the Ocean (GECCO) consortium (Köhl and Stammer 2008) for 1952 to 2001 finds the increase in thermosteric sea level rise on average about double that of Levitus et al. (2000). It amounts to 1.2 mm yr^{-1} over the top 750 m and 1.8 mm yr^{-1} over the total water column from 1992 to 2001, which corresponds to a heat flux into the ocean of 1.5 W m^{-2}. However, the global freshwater flux and salinity are not well constrained by observations, and results depend on the deep ocean trends that are also poorly constrained by observations. The 1.5 W m^{-2} gain in ocean heat corresponds to a global value of 1.05 W m^{-2} and is slightly high compared with the Fasullo and Trenberth (2008a) estimate for 2001-2004 of 0.9 W m^{-2}.

Contributions to sea level rise. From 1992 to 2003, a reasonable accounting of sea level by IPCC (2007) suggested about 60% was from thermosteric effects while 40% were from eustatic contributions from melting land ice. Since then the proportions have changed and a balance has been much harder to achieve.

For the mid-2003 to 2008 period, abundant data exist on changes in both ocean heat content from ARGO floats down to 900 m (and XBT data can be omitted) and ocean mass from Gravity Recovery and Climate Experiment (GRACE) gravity satellite measurements. Their sum should amount to the sea level from altimetry estimates from satellites, but substantial discrepancies between trends of ~2 mm/yr were found (Willis et al. 2008). Part of this discrepancy can be accounted for by improved land-sea masks and better resolution in the GRACE measurements. One claim to resolve the discrepancies through increased contributions from melting land ice of 2 mm/yr for 2003 to 2008 is based on an alternative GRACE data analysis that includes a substantial Glacial Isostatic Adjustment (Cazenave et al. 2009). Leuliette and Miller (2009) also claim to have closed the sea level budget by increasing the ocean expansion component. The steric contributions range from -0.5±0.5 mm/yr for mid 2003 to mid 2007 (Willis et al. 2008) to 0.4±0.1 mm/yr (Cazenave et al. 2009) to 0.8±0.8 mm/yr (Leuliette and Miller 2009) for 2004 to mid-2008 (with 95% confidence limits).

Summary comments. Clearly the ARGO floats plus fixed moored arrays (such as the TAO/TRITON array in the tropical Pacific) are a boon to addressing the ocean spatial sampling problem that is prevalent prior to about 2002, and they also address the much needed measurements of salinity, so that the expectation is for enormous positive impact. Nonetheless, preliminary processing of ARGO data indicates that it is not without problems associated with different calibration and manufacturers of the instruments; a problem common for atmospheric measurements. Future sea level rise and whether or not the rate is increasing are vital issues for climate change as they can have huge impacts on small island states and coastal regions. Biggest impacts on coastal erosion and flooding occur through combinations of high tide and storm surges on top of the rising sea level.

6. The ocean and hurricanes

The record breaking hurricane season in the North Atlantic in 2005 highlighted several issues of importance to oceanography. The 2005 season had the largest number of named storms (28), the largest number of hurricanes (15), the only time 4 category 5 storms have occurred, the most intense storm (Wilma, 882 hPa central pressure), the most intense hurricane in the Gulf of Mexico (Rita, 897 hPa), and the most damaging hurricane on record (Katrina), the latter of which was the deadliest in the U.S. since 1928. Observed and potential changes in hurricanes with global warming are discussed in detail in Trenberth (2005), Emanuel (2005) and Webster et al. (2005) who show that intense storms globally are observed to be increasing, in line with theoretical and modeling expectations and, in particular, in ways strongly related to SSTs. There are concerns over the quality of the "best track" data. Nonetheless, the IPCC (2007) assessment aptly summarizes the situation as follows: "There is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures. There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. There is no clear trend in the annual numbers of tropical cyclones."

During a tropical storm, strong surface winds not only take heat out of the ocean at rates of order up to about 2000 W m^{-2}, but also mix the ocean through tens to hundreds of meters, cooling the surface and creating a cold wake (e.g., Walker et al., 2005; Trenberth et al. 2007b; Trenberth and Fasullo 2007). Hence the tropical storm activity depends critically not only on SSTs but also subsurface temperatures, especially for whether the ocean environment is favorable for the next storm and thus an entire active season. The so-called warm and deep "Loop Current" in the Gulf of Mexico appeared to play key role in the intensification of Ivan (e.g., Walker et al. 2005), Katrina, and Rita (Trenberth et al. 2007b; Trenberth and Fasullo 2008). Increasing evidence suggests that predicting hurricanes requires an ocean model to allow these feedbacks on hurricanes to be included. However, surface fluxes are highly uncertain for winds over about 20 m s^{-1} especially concerning the role of ocean spray in exchanging heat and moisture between the ocean and atmosphere, and ocean mixing is also uncertain. Moreover, the role of the hurricane-induced mixing in the ocean on currents and the thermohaline circulation (Boos et al. 2004) are major unresolved issues that could change our views of how future climate may change, as current climate models do not include these processes.

7. Why are we observing the ocean?

The above describes the critical role of the oceans in climate. Oceans take up heat in the summer half year and release it in winter, playing a major role in moderating climate. The oceans play a crucial role in ENSO. However, the enormous heat capacity of the oceans means that the oceans also play a key role on decadal and longer timescales. The exact role of the oceans in the North Atlantic Oscillation is being explored. Variations in the ocean affect ecosystems, including fisheries, which are of direct importance for food and the economy. It is therefore important to track the changes in ocean heat storage, as well as the uptake and release of heat in the oceans through the surface fluxes. Salinity effects on ocean density are also important but have been poorly measured, although ARGO profiles will help enormously. It is essential to be able to attribute changes in ocean heat content and the mass of the ocean to causes (such as changing atmospheric composition), using models. Climate models suggest that the MOC could slow down as global warming progresses owing to warming and freshening of the high latitude ocean, resulting in counter-intuitive regional relative cooling in the North Atlantic region on multi-decadal time-scales (IPCC 2007).

It is vital to establish a baseline of the current state of the ocean as a reference for future assessments. Monitoring of the top 500 m of the tropical Pacific Ocean has been established because of ENSO. It is an excellent start. The World Ocean Circulation Experiment (WOCE) has paved the way. Increasing attention will be devoted to measurements of the biogeochemistry of the oceans and especially the carbon cycle, and possible feedbacks on carbon dioxide levels in the atmosphere. Relationships of physical ocean changes to ecosystems and fish stocks will enable improved fishery management. Observing technologies are evolving, and plans are already well underway for an initial ocean observing system and, while substantial progress has been achieved, it has yet to be fully implemented. The observing system must evolve in ways that protect the integrity and continuity of the climate record. Such a system must be linked to comprehensive analysis capabilities of not only the ocean, but also the atmosphere, sea ice, radiation, precipitation, and other ingredients in the climate system. From time to time it is expected that reanalyses of the past ocean and climate record will be desirable as improvements are made in models and data assimilation systems. Tracking the performance of the observing system to ensure that it is meeting needs is another necessary component (Trenberth et al. 2002a). With such information, good models will be enabled to make skilful predictions of climate on timescales ranging from weeks, to interannual (ENSO), to decades in a seamless way. However, good ocean observations are also essential for improving models.

Ongoing assessments are therefore required of the continually changing state of the ocean, as well as our ability to observe it and assess what is going on. It is therefore appropriate for NOAA to carry out an annual assessment of both the state of the ocean and the state of the observing system, examine how well needs are being met, and find timely remedies for inadequacies. It is also vital to ensure that the observations are analyzed, and products generated to begin to address the issues outlined above. This synthesis phase is important for scientists, but it is essential to justify the ongoing costs of the observing system to taxpayers. Indeed, the increased knowledge and benefits in improved decision making will surely greatly exceed the costs.

8. How are we observing the ocean?

It has been a challenge to observe the whole ocean, globally and throughout its depth on the appropriate time scales. The traditional approach of using observations from ships is expensive and inherently limited in spatial and temporal scope. Moored and autonomous drifting buoys have revolutionized the observing system capabilities and made a global system possible. Space-based observations of sea level through altimetry, ocean color, surface wind stress through scatterometry and other passive sensing, SST through infrared (skin, clear sky) and microwave (1 cm bulk, all weather) techniques, precipitation through the Tropical Rainfall Measurement Mission (TRMM) using passive and active radar systems have been established but are largely confined to surface variables, so that in situ observations provide an essential complement. Future missions on salinity will expand capabilities. NOAA has been the main agency for routine in situ observations using diverse but complementary networks of systems (Chapter 3) that are designed to take optimal advantage of opportunities for observations at minimal expense. The mix is likely to change over time as technologies become more sophisticated and developed. Consequently synthesis of all the observations in a physical framework (using models; e.g., Köhl and Stammer 2008) is an essential step in the overall process of determining the state of the ocean, and continuity of record is a major challenge.

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